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DISCUSSION OF ORIGIN AND SIGNIFICANCE OF OPENWORK GRAVEL

(Published in May, 1950)

By Jacob Feld, A. Casagrande, A. Mayer, H. Cambefort, Hyde Forbes, L. F. Harza, and Allen S. Cary

POWER DIVISION

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DISCUSSION

JACOB FELD,[10] M. ASCE.—Gravel formations of the type described by the author require special treatment in engineering design. The number of places on the eastern seaboard where material of this nature is found seems to indicate that openwork gravel is not an unusual soil condition. The engineering significance of three occurrences are described herewith showing the variety of nature and probable origin.

West of the Neversink River in the valley north of Port Jervis, N. Y., a very deep layer of clean, rather large-sized gravel is found at depths of from only 2 ft to 3 ft below the surface. The gravel runs from 1 in. to 6 in. deep, and is overlain with sand and with a very scant top soil cover. About 1925, two branches of the near-by Martin Creek were dammed up to provide recreational lakes. The bottoms of the lake areas were covered with local clay and river mud to form an impervious skin and were surfaced with sand. The dams themselves were built of local gravel blended with run-of-bank sand to reduce porosity; they were blanketed on the upstream side with a 12-in. layer of selected clay, protected by hand-laid riprap filled with sand. The top of the dam forms a roadway and, because the gravel is fairly well meshed, very little settlement has occurred; strangely enough, little seepage has been lost through the dams.

In this same area an attempt made to sink well points for developing a water system supply proved impossible because of the large void spaces, and actual wells had to be dug by excavation. In this vicinity, the gravel is apparently the result of flood deposition by the Neversink River and has been brought down from the Catskill Mountain areas. Individual stones are smooth and show no pitting.

In the immediate vicinity of Piney Branch of the Rock Creek near Sixteenth Street in Washington, D. C., there is a layer of openwork gravel extending from about 8 ft to 10 ft below street grade to a depth of at least 30 ft. This gravel varies in size from $\frac{1}{4}$ in. to 6 in., and individual stones tend to be flat. A rather thin coating of silt has been deposited in the void spaces. Again the gravel is evidently the result of deposition by river floods, and later flooding has left the thin coat of silt. Because of the rather large percentage of voids, the question arose as to the proper bearing capacity of this gravel for the support of a large building structure. Load tests on an area of 4 sq ft indicated that, up to a loading of 8 tons per sq ft (at the end of the tests), practically no settlement occurred beyond the elastic deformation of the testing frame. This gravel stands up vertically for several months even during considerable temperature changes and heavy rainfall. The individual stones are mostly limestone and sandstone in origin, thus explaining the tendency for flat shapes.

On the southern slope of the terminal moraine in northern Long Island (N. Y.), especially on the westerly end of that strip, there are numerous exposures of layers of openwork gravel, each layer consisting of different size

NOTE.—This paper by Allen S. Cary was published in May, 1950, as *Proceedings-Separate No. 17*. The numbering of footnotes, illustrations, and tables in this Separate is a continuation of the consecutive numbering used in the original paper.

[10] Cons. Engr., New York, N. Y.

ranges. The sizes range from very small, almost sand size, to a 1-in. gravel. These are definitely glacial depositions and the individual particles are completely clean of any later deposition. As a result the different layers are quite loose. The load test made on 4 sq ft of these materials indicates a continuous lateral flow and settlements of more than 1½in where 4 tons per sq ft is applied. This is the type of material that flows away from loads and causes rolling equipment to bog down very readily, both when wet and when dry.

The foregoing examples indicate a variety of structural characteristics of open-gravel depositions and the discussion is written to point out that no general conclusions should be drawn for the necessary and proper use of these materials in engineering design.

A. CASAGRANDE,[11] M. ASCE.—The writer recalls with pleasure the stimulating discussions which he had with the author and his colleagues on the mystery of the shrinkage cracks in the clay that fills the voids in the openwork gravel at the Chief Joseph dam site in Washington. While reading Mr. Cary's highly interesting paper the writer thought of still another explanation for these open fissures in the clay—namely, the possibility that they are due to ice segregation in the clay which developed while the gravel was covered by a glacier.

For several reasons the writer is now inclined toward the hypothesis that the clay was carried in and deposited by water seeping through the pores, rather than by intrusion of an overlying clay layer which was forced into the voids by the weight of a thick layer of ice. In order to admit the intrusion hypothesis from the standpoint of soil mechanics, one would have to assume that the clay layer existed in an extremely soft condition and that a heavy load of till and ice was deposited so quickly that the clay could not have had time to consolidate materially. At the slow normal rates of load application the clay would certainly have consolidated into a stiff consistency without flowing to any appreciable extent into the voids of the gravel. The writer believes that this could be proved by laboratory tests.

It is true that the clay deposit in the voids is fairly stiff; but the high water content indicates that it would be possible to deposit the clay by sedimentation from percolating water, with much of the strength developed after deposition by thixotropy.

The author suggests that it is difficult to visualize how the pores could have been filled by clay as a result of infiltration. However, the writer has seen stiff, highly plastic clay that completely filled solution channels in limestone; and there is no doubt that the clay had been deposited from circulating water.

In the case of the openwork gravel, it would seem possible also that the original deposit of fines in the voids of the gravel was of nonplastic character, and that it filled the voids only partly, but that particles of volcanic ash disintegrated in the course of time to form the present contents of montmorillonite. As a result of such chemical breakdown the material in the voids changed into a clay which could easily have filled the entire volume of the voids. Moreover, because of the limitation in volume expansion within the voids of the gravel, it is

[11] Prof. of Soil Mechanics and Foundation Eng., Harvard Univ., Cambridge, Mass.

conceivable that such a clay filler could exist even with a stiffer consistency than the clay in the openwork gravel under discussion.

The network of fissures and open spaces surrounding the pebbles resembles closely the network of ice which would form in the clay if the entire mass were frozen. Is it not conceivable that during the long period that a glacier covered this site, the entire stratum of openwork gravel was frozen? This would fully explain this network of "shrinkage cracks." Once a thixotropic clay is consolidated to a given stress (in this case the stresses resulting from ice segregation), removal of the stress (that is, melting of the network of ice in the clay) would not cause the clay to swell sufficiently to close the open fissures. Even in ordinary clays which have been frozen, one finds after thawing that the spaces which were filled with ice remain open and clearly visible for some time. However, in contrast to the clay in the openwork gravel, where the weight of the overlying material is carried entirely by the gravel, the open spaces in an ordinary clay layer are usually soon closed again due to the weight of overlying material.

The "flow lines" which Mr. Cary describes and illustrates in Fig. 7 can also be explained by frost action. Since frost penetrates much faster through the pebbles than through the clay (the freezing of water slows down the progress within the clay), freezing of the clay in the narrow passages would proceed chiefly from the walls of the pebbles toward the middle of the voids and would result in ice layers directly adjoining and parallel to the surface of the pebbles, with occasional transverse ice layers. In addition, the clay will form a laminated structure perpendicular to the direction of withdrawal of water by ice segregation—that is, in the narrow passages parallel to the surface of the pebbles. The formation of such a laminated pattern in clays due to consolidation has been described by M. Juul Hvorslev,[12] Assoc. M. ASCE, who attributed this phenomenon to orientation of the flaky particles perpendicular to the direction of the major principal stress. Later, L. Casagrande demonstrated that a laminated structure in clays can result from the formation of fissures caused by pore water flow. Such fissures develop perpendicular to the direction of flow and have been observed to form when very steep hydraulic or electro-osmotic gradients are created. Assuming the freezing hypothesis to be correct, steep hydraulic gradients must have developed in the clay adjacent to the growing ice lenses.

The question might be raised as to why effects of freezing of sediments underlying glaciers have not been observed in other cases. Probably the reason is that in the case of the openwork gravel thawing could take place without overlying weight recompressing the spaces which were occupied by ice layers, a condition which would normally not be fulfilled in other materials. Besides, it is possible that ice segregation in fine-grained soils, subjected to the very great load of an ice sheet, is much less pronounced and may even be entirely absent. The clay in the voids of the openwork gravel was protected from these high stresses because they were carried by the gravel itself.

The writer believes that his hypothesis could be checked by freezing tests on artificial specimens of an openwork gravel whose voids are filled with soft clay.

[12] "Über die Festigkeitseigenschaften Gestörter Bindiger Böden," by M. Juul Hvorslev, *Ingeniørvidenskabelige Skrifter, A. No. 45*, Danmarks Naturvidenskabelige Samfund, København, 1937, pp. 11–14.

A. MAYER,[13] M. ASCE.—In connection with the subject of this paper, the writer recalls two instances in which openwork gravel was encountered. The first was that of a morainic deposit on the north bank of the Sautet reservoir in France. Its existence was well known from the very beginning of the dam studies. All the surveys had shown that the river had once followed a different course. The original valley had been filled by a morainic deposit, and the river had found its way through a fissured part of the limestone ridge to the lowlands. The question as to whether this sand and gravel mass would be watertight was investigated by several experts, who were all of the opinion that its thickness (approximately 1.5 miles) would suffice to prevent any appreciable percolation.

The dam was built and the reservoir was filled for the first time. By that time, everyone had forgotten about the gravelly layers, until several trees began to slide into a valley 1.5 miles away from the reservoir. Wells appeared which had never existed previously, and measurements showed that after a few days the total flow from them exceeded 1 cm per sec.

The head of the water in the reservoir did not exceed 100 ft above the level of the wells, corresponding to a hydraulic gradient of 1.5%. The filling of the reservoir was stopped and investigations were begun. Open pits sunk into the morainic material showed that it was composed of alternate layers of mixed sand and gravel and what Mr. Cary calls openwork gravel—that is, gravel layers without any binder. The trouble was that the original river bed, filled with these deposits, had a width of several hundred feet. Although the volume of the percolating water was not very important, the prevention of the leakage proved to be a difficult task. The first method was cement grouting. A large number of bore holes were sunk and a great volume of cement was pumped in, but without any result. The voids were much too large to be stopped with cement. Further investigations showed that the cement grout had passed through the largest voids and assembled in horizontal lenses. In some cases it had percolated into the reservoir.

Several attempts were made to silt the slope progressively. The tests were stopped as soon as the flow stopped decreasing. (In the writer's opinion, these tests would probably have given good results if they had been made more systematically and on a sufficiently large scale.) Grouting tests were then made with stabilized clay.[14] Preliminary tests, between a bore hole and an open pit, showed that a heavy grout of stabilized clay did not penetrate the sand and gravel layers; it percolated through the openwork gravel, and made it absolutely watertight when continued long enough. A number of holes were thus grouted and the total flow decreased 50%; but the cost of the borings was high, and the company that owned the dam decided to stop the work. Anyhow the experience showed that there was a way to prevent the seepage in case the total flow had increased; in fact, it remained constant. Since then, the percolation has continued at the same rate of from 1 cm per sec to 2 cm per sec according to the level in the reservoir. Some day, it may appear economical to close this gap; the technical means for doing so are available.

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[13] Ingénieur Général des Mines, Ministère de la Production Industrielle, Paris, France.

[14] "Dispositions les plus recentes pour empecher la formation des renards," by A. Mayer, Report to the Third Congress on Large Dams, Stockholm, June, 1948, Rept. 22, Question 10.

Another case of openwork gravel was met during the construction of the diversion canal at the Donzères-Mondragon dam site, in the Rhone Valley. This canal had to be dug through the alluvial deposits of the valley, for a distance of several miles. As the work began the gravel layers appeared to be composed of very distinct horizontal strata, some of them being quite characteristic of openwork gravel. The loss of water through these layers was very important. Tests were started to find an economical way to stop the flow. Excellent results could be obtained by simply plowing up and compacting the slopes of the cut, so as to have a graded mix covering up the openings of the gravel layers. This method also would very likely have been efficient in the previous case if applied on a sufficiently large surface and if the water had been silty enough to seal off the blanket progressively.

These two cases have been mentioned to emphasize the fact that openwork gravel is of very great significance to foundation engineers and its presence must be taken into account in all cases involving water flow. Therefore the writer is thankful to Mr. Cary for his very excellent paper. The flow through openwork gravel can be stopped, in all cases, by stabilized clay grouting. In some cases, simpler surface treatments may be sufficient to give quite sufficient results.

H. CAMBEFORT.[15]—Numerous studies in France have led engineers and geologists to believe that openwork gravel can be found in all normal alluvial deposits. Such gravel has been observed in the valleys of numerous large rivers—the Garonne River at Saint-Martory, the Rhône River at Donzère, and the Rhine River at Ottmarsheim—as well as in valleys of rivers of moderate size—the Durance River at Serre Poncon and Lamanon, the Drac River at Le Sautet and Monteynard, the Arc River at Aiguebelle, the Isère River at Aigueblanche, and the Fensch River at Hayange.

The type of alluvium in which openwork gravel is found is characterized by successive strata of highly distinctive grain size. For example, the sand strata will have grains smaller than 1 mm whereas the gravel beds will contain no pebbles smaller than 5 mm. Gravel beds generally occur in strata only a few centimeters thick. Each pebble is covered with a thin film of yellow when ferric oxide and of black when manganese oxide. The presence of oxides testifies that the pebble strata are the preferred channels for underground courses.

Sometimes (as at Ottmarsheim) the voids in the gravel are filled with fine sand identical with that in contiguous strata; but voids filled with clay as described by the author have never been reported in France. It is possible that the interstitial sand comes from a secondary deposition. For some reason, the entire openwork gravel stratum is never completely filled.

The engineer, however, is not concerned so much with the origin of these deposits as he is with their degree of heterogeneity. For this reason, observations on gravel size and the permeability of alluviums are most important. Each time that the writer was able to obtain some truly clean samples from the original deposits, the resulting grain-size curve, plotted on Gaussian logarithmic

[15] Civ. Engr., École Nationale des Ponts et Chaussées, and Head, Dept. for Studies of Constr., Entreprise de Fondations et Travaux Hydrauliques, Paris, France.

graph paper, was a straight line (see Fig. 8(*a*)). Thus, the gradation of these deposits conforms to Gibrat's law of the proportionality of pebble diameters. On the other hand, if the grain size of a mixture of the deposits is analyzed, the gradations also plot as straight lines, as shown in Fig. 8(*b*).

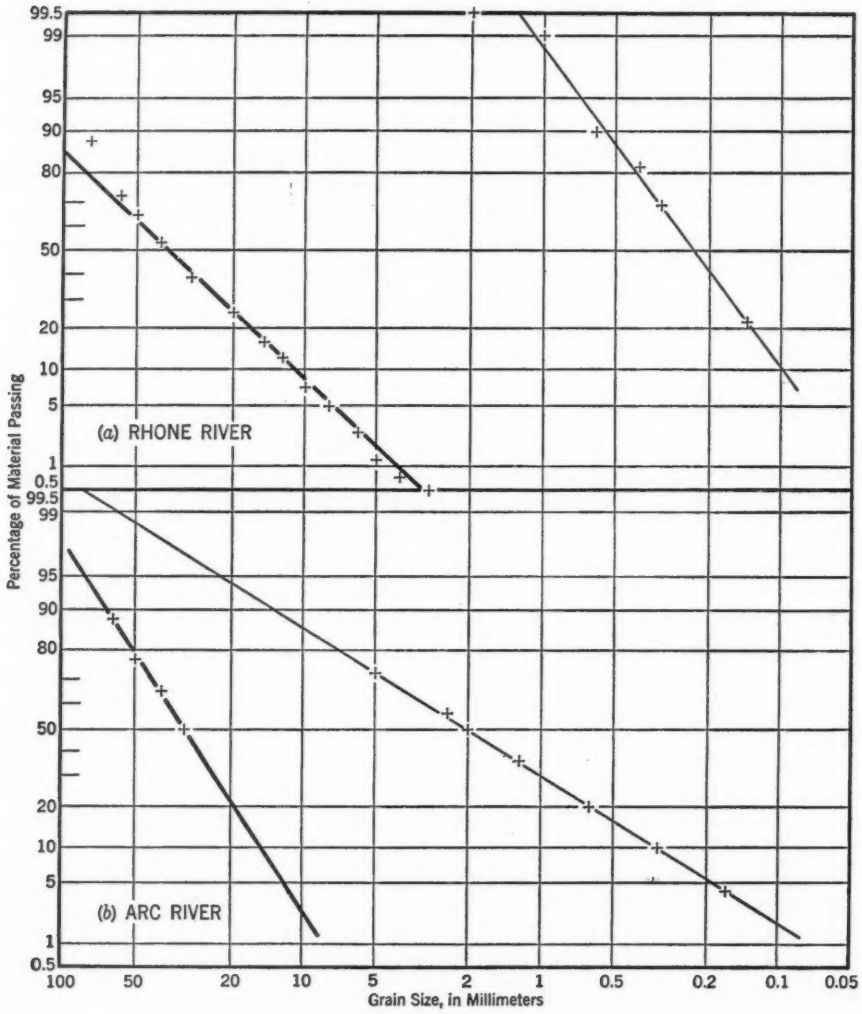

FIG. 8.—GRAIN SIZES OF ALLUVIUM SAMPLES

This fact permits engineers to judge the relative heterogeneity of the alluviums without recourse to extensive excavation. For a complete determination of heterogeneity, however, it is necessary to study the flow of ground water or to use "pumping-in" tests, and to decide whether the permeability measured "in place" corresponds to that estimated from the gradation curves. For example,

observation of annual graphs for the Sautet reservoir on the Drac River presented the seepage from the neighboring valley of the Sézia River as a function of the lake level. After a lapse of several days the maximum and minimum lake levels were reflected in the seepage from the Drac River. Thus it was possible to compute the speed of the actual flow; and, from that flow, the permeability of the material in the ground-water passageway.

The path of percolation was about 1,200 m (about 4,000 ft) which indicates a permeability of about 2×10^{-2} m per sec (about 3.94 ft per min). (Contrary to a widely accepted opinion, the flows through these open structures are often laminar, as can be shown easily in the present case.) This value is obviously less than the permeability that can be estimated as logical under the circumstances—that is, a value of from 1×10^{-1} m per sec to 5×10^{-1} m per sec (from about 20 ft per min to 100 ft per min). Probably the disparity is explained by the distribution of the gravel in lenticular layers, which are more or less connected with each other. On the other hand, if the average permeability of the formation is determined, this time taking the total leakage into account, the flow is computed as approximately 3×10^{-3} m per sec (0.53 ft per min).

The foregoing comparison of ground flows shows that an average of 15% of the area exposed to percolation pressure offers a free channel for seepage. This ratio is plausible.

Even if openwork gravel deposits are not directly interconnected, they do increase the ease with which water can circulate through the alluviums. To reduce this circulation it is necessary to:

(1) Inject grout into all the large passages;
(2) Modify the direction of flow, forcing it in a direction perpendicular to the layers of the deposit; or
(3) Homogenize the entire deposit to a predetermined thickness.

In general, with a simple field test boring of large diameter (at least 400 mm or 16 in.) it is possible to determine the voids characteristics of alluviums; but the borings and water tests should be entrusted only to an engineer who is capable of interpreting the phenomena correctly during the course of the test.

HYDE FORBES,[16] M. ASCE.—The paper describes the occurrence of lenses of clean gravel in alluvial deposits, with the usual heterogeneous mixture of varying grain sizes, and suggests the way they were deposited. That such an occurrence is unusual is attested by the yield of wells bored in alluvial deposits of valleys. This phenomenon has not been encountered by the writer in the interior valleys or in the coastal plain of California, or in southwestern Arizona, although many penetration records of well bores and yield on pumping in these areas have been made available to him. However, such a deposit was encountered adjacent to the Columbia River channel in the vicinity of the Hanford area in Washington (mentioned by the author), and its effect on well yields may be of interest.

In connection with the development of a water supply for the construction camp at Hanford in 1944, about twenty-four test bores, 6 in. in diameter, were

[16] Cons. Engr and Geologist, Palo Alto, Calif.

drilled between a bedrock promontory and the channel of the Columbia River. About half of these were developed into operating wells having larger diameter casings with depths varying from 54 ft to 121 ft. When the development was completed, pump capacity was installed on the basis of the completion tests, and thereafter records of discharge and drawdown were kept. Typical examples are given in Table 1(*a*), the wells being within from 1,500 ft to 5,000 ft from the river. The depths of the wells were dictated by the elevation at which the lacustrine clay beds were encountered under the flood plain alluvium. Specific yields in excess of 1,000 gal per foot of drawdown for such shallow wells have not been found at other locations within the writer's experience. In

TABLE 1.—EXAMPLES OF DISCHARGE AND DRAWDOWN RECORDS IN OPENWORK GRAVEL

Diameter of casing (in.)	Depths (Ft)		Safe yield (gal per min)	Drawdown (ft)	Yield (Gal per Min)	
	Total	Below water table			Per foot of drawdown	Per square inch[a]
(1)	(2)	(3)	(4)	(5)	(6)	(7)
(*a*) Hanford Area in Washington						
12	100	34	425	1.5	283	1.4
12	54	50	430	2.0	215	1.4
12	65	45	700	0.7	1,000	....
24	60	33	825	7.5	109	8.3
16	90	79	650	3.0	227	2.2
18	90	79	650	0.2	3,250	9.3
18	92	89	2,000	3.0	733	3.0
16	121	68	1,000	0.20	5,000	1.0
20	84	76	1,400	0.75	1,850	2.0
14	55	46	1,200	1.2	1,000	2.0
(*b*) Richland, Wash.						
12	62	31	470	18.9	25.0	1.4
18	72	63	2,266	33.3	68.0	3.2
18	72	58	2,575	30.2	85.0	4.1
14	78	60	1,500	27.8	54.0	2.7
14	80	60	920	25.8	36.0	2.1

[a] Yield, in gallons per minute per square inch of perforation.

addition, such yields were not found for the wells drilled at, and north of, Richland, Wash., from 20 miles to 30 miles downstream, for the water supply of the town. There the Columbia River eroded well below its previously deposited alluvium into the lacustrine clays and the water table slopes toward, instead of from, the river. Typical data for the Richland wells are listed in Table 1(*b*). It is apparent that a special condition exists in the recent depositions of the Columbia River over its flood plain north and east of Gable Mountain near Hanford. The following were assumed necessary for the formation of large gravel bars in the stream channel to become part of the flood plain as the channel shifted in aggradation; namely,

(1) River stages and a velocity that would move the mass by bed rolling and keep it clear of fines;

(2) Sudden changes in river stage and velocity favoring deposition choking the channel and forcing the stream out of its banks allowing rapid burial of the masses of gravel;

(3) A source of abundant gravel composed of hard rock resistant to disintegration and decomposition, such as would be found in watersheds containing many glaciers; and

(4) Masses (condition No. 3) continuous with or directly connected with similar masses underlying the present stream channel.

L. F. HARZA,[17] M. ASCE.—This interesting paper does well to call attention to the possibility of a nearly continuous succession of lenticular bodies of open-void gravel (the term preferred by the writer) which might entail important leakage to a dam foundation or abutment if not intercepted by a cutoff. This is a possibility but a rather remote one in large dams where seepage distances are great and many variations in material along any seepage route are probable.

Normal gravel should never be a reason for alarm as it would be tighter than an equal volume of sand of the same character as that which fills the voids of the gravel. It is only the open-void gravel which might cause concern or require grouting.

The important problem to the engineer is how to detect such a condition of open voids in invisible locations and how to correct it. Under the heading "Engineering Significance of Openwork Gravel: Water Jetting," the author points out that a pipe can be jetted down through "normal" or what might be called "graded" or "void-filled" (preferred term) gravel, but will not penetrate open-void gravel which forms "an impassable barrier to jet pipes." This fact suggests a method of detecting its presence, but not its continuity—which is of far greater importance. Isolated lenses would not be harmful. Many jet pipe tests over the foundation area, revealing open-void gravel at consistent depths, might imply communication, but actual water tests would be necessary to confirm such a suspicion. The open-void gravel in the abutment of the Chief Joseph Dam site is under a great depth of glacial drift. This is an exceptional condition which would be difficult to explore from the surface.

Even where continuity of open-void gravel is indicated, it could probably be grouted with cement or clay grout. Void-filled gravels do not accept grout, except the so-called "chemical" type; but open-void gravel by its very nature should be susceptible to grouting as much so as the gravel used in the Prepakt method.

At one time a masonry cutoff to sound rock and a masonry core wall were considered essential for any earth dam. This requirement has given way by gradual stages to earth cutoff and core and, where rock is too deep to reach by excavation, to a sheet pile cutoff with earth core above, or, rarely, to other expedients. Within recent years high earth dams on deep foundations without any cutoff have proved successful. The outstanding example is the Davis Dam

[17] Harza Eng. Co., Cons. Engrs., Chicago, Ill.

in Arizona-Nevada. The Fort Randall Dam (in South Dakota) will also rest on a deep sand bed of the Missouri River without cutoff, depending on a long path of travel of some 3,000 ft, or about 5% water gradient, through the sand to reduce the seepage to an acceptable amount. Sheet pile cutoffs may be assumed to be utilized even less frequently as experience accumulates and as confidence is gained in dams without such cutoffs. This trend, however, will emphasize the need to detect and grout any open-void gravel.

ALLEN S. CARY,[18] ASSOC. M. ASCE.—The wide distribution of openwork gravel is indicated by the geographical location of those who so kindly discussed the paper. The fact that each instance cited happens to be in a glaciated area further confirms the statement that openwork gravel is found more frequently in such areas than in unglaciated areas.

Mr. Feld's discussion regarding the wide range of bearing values of individual deposits is a worthwhile contribution.

The interesting discussion by Mr. Casagrande should serve as a warning, particularly to geologists, that the simplest, most obvious explanation for a natural phenomenon is not necessarily the actual one. The writer does not have sufficient familiarity with frost action in clay masses to discuss Mr. Casagrande's hypothesis intelligently. Laboratory tests should certainly resolve the question. Unfortunately, for the soils engineer and geologist the questions of origins are not of particular engineering significance, and funds for the necessary research are not readily available.

The discussion by Mr. Mayer concerning the Sautet Reservoir in France is interesting since this reservoir has its counterpart in a small reservoir in the State of Washington. However, the significance of the openwork gravel was not recognized in Washington until after the reservoir was filled when leakage downward into the gravel became excessive and an impervious blanket over the exposed gravel became necessary.

Mr. Cambefort has again emphasized the engineering significance of openwork gravel where water is involved and suggests means of determining the corrective steps necessary.

Mr. Forbes shows that openwork gravel has certain very distinct advantages if it lies below the ground-water table and one is looking for large quantities of well water.

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[18] Senior Geologist, Seattle Dist., Corps of Engrs., U. S. Army, Seattle, Wash.

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